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Alternative and Opportunity Dryland Crops and Related Soil Conditions in the Southern Great Plains

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ABSTRACT

Dryland winter wheat (*Triticum aestivum* L.) and grain sorghum [*Sorghum bicolor* (L.) Moench] yield favorably when rotated or grown continually in the southern Great Plains, but improved water conservation practices make other systems possible for these crops. Also, farmers can now produce other crops without losing government payments. Winter wheat, grain sorghum, and opportunity crop performance; alternative crop adaptability; and system effects on soil properties were determined. Wheat yielded 1.82 Mg ha^{-1} when rotated with grain sorghum or fall canola (*Brassica napus* L.) and 1.21 Mg ha^{-1} when grown continually or rotated with spring canola. Soil water contents at planting resulted in the differences. Grain sorghum yielded 2.89 and 3.02 Mg ha^{-1} when rotated with wheat or grown continually and 2.24 Mg ha^{-1} when rotated with kenaf (*Hibiscus cannabinus* L.), although water contents at planting were similar. Kenaf produced only 2.3 Mg ha^{-1} plant material, but contained 327 g kg^{-1} protein at 32 d after planting and 195 g kg^{-1} when killed by frost. Canola crops failed. Triticale (× *Triticosecale* Wittmack) produced more forage, but less grain than wheat. Soil water contents at planting and precipitation strongly influenced opportunity crop yields. Mean soil C contents increased from 5.52 to 5.94 g kg^{-1} during the study. Aggregate diameters and percentages <0.25 mm in diameter showed no definite trends. Few bulk density and no aggregate water stability results differed. Some alternative and opportunity crops produced favorably, but generally no better than wheat or grain sorghum.

Winter wheat and grain sorghum are well-adapted dryland crops for the semiarid southern Great Plains. Each performs well when grown continually or when combined in a rotation. Although total grain production was greatest when grain sorghum was grown continually in the southern Great Plains (Jones and Popham, 1997), weed problems sometimes develop that severely limit grain yields. Severe weed problems sometimes also develop with continual cropping of winter wheat. Besides potential weed problems, continual cropping provides for little time between crop harvesting and planting of the next crop, which often results in low amounts of stored soil water for crop use. Dryland crop yields depend strongly on stored soil water (Jones and Hauser, 1975; Jones and Popham, 1997; Unger, 1978). Of course, adequate and timely precipitation is important also for successful dryland crop production in a semiarid region.

Growing the crops in a rotation (wheat–fallow–sorghum–fallow, designated WSF) provides an opportunity to control problem weeds for each crop during the fallow period after harvesting. The longer interval between crops also provides more time for storing soil water, thus reducing the risk of low yields such as those associated with continual cropping (Greb, 1983; Haas et al., 1974; Jones and Johnson, 1983). A disadvantage of the WSF rotation is that it results in only two crops in 3 yr. However, if crop yields can be increased sufficiently because of greater soil water storage resulting from the longer fallow period, then use of the rotation may be an economical improvement over continual cropping (Mathews, 1951; Unger, 1983). Use of the rotation also reduces seed, planting, and harvesting costs because they are incurred less frequently (twice in 3 yr) than with continual cropping (once each year).

Although the WSF rotation is well suited for grain sorghum and winter wheat production in the southern Great Plains, the availability of improved water conservation practices suggests other cropping systems may be suitable for dryland crop production in the region. Also, other crops may be adaptable to the region, and producers now have greater freedom regarding crops they can produce because of federal farm policies (Federal Register, 1996).

Sunflower (*Helianthus annuus* L.) and cotton (*Gossypium hirsutum* L.) are well-adapted dryland crops in the region (sunflower throughout the region and cotton mainly in the southern portion of the region) (Jones and Johnson, 1983). Little or no information is available, however, regarding crops such as kenaf, canola, pinto bean (*Phaseolus vulgaris* L.), forage sorghum (*Sorghum* spp.), pearl millet [*Pennisetum glaucum* (L.) R. Br.], oat (*Avena sativa* L.), and triticale under dryland conditions in the region. These crops have some traits that could make them adaptable to the region, provided production levels are adequate and suitable markets became available. Kenaf has a high protein content (Nielsen, 1998; Phillips et al., 1996; Webber, 1993), which could benefit the cattle (*Bos taurus*) production industry in the region. Also, a part of kenaf stems is suitable for paper production, which could result in the crop becoming a renewable source of material for the paper industry (Webber, 1993). Canola produces a high-quality oil (Francois, 1994) that is used for food preparation and human consumption (margarine, salad dressing, etc.). Pinto bean is widely used as food for humans. Forage sorghum, millet, oat, and triticale are used for grazing by cattle or as hay crops; oat and triticale also are grain crops. As compared with winter wheat, which is widely grown in the region for grazing by cattle, some varieties of triticale have potential to extend the grazing season

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Abbreviations: WSF, wheat–fallow–sorghum–fallow; GS–K, grain sorghum–kenaf; FC–W, fall canola–wheat; SC–W, spring canola–wheat; CGS, continual grain sorghum; CW, continual wheat; CT, continual triticale; OC-1, OC-2, and OC-3, opportunity cropping Series 1, 2, and 3; SOCC, soil organic carbon concentration; MWD, mean weight diameter; WF, wheat–fallow; LSD, least significant difference; WUE, water use efficiency.

into late spring or early summer because they mature later than wheat (Miller et al., 1993).

Objectives of this dryland study were to (i) evaluate grain sorghum and winter wheat production in various cropping systems, (ii) determine the adaptability of several crops besides grain sorghum and winter wheat to the region, (iii) evaluate opportunity cropping as a means to increase overall productivity, and (iv) determine effects of the different systems on soil water storage and use, organic C concentration, bulk density, and aggregation.

MATERIALS AND METHODS

The study was conducted on Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustoll) at the USDA-ARS Conservation and Production Research Laboratory, Bushland, TX. Bushland is at 35°11′N and 102°5′W, and 1180 m above mean sea level. Plots were 8 m wide and 42 m long, level, and separated lengthwise by berms. In addition, a berm at one end prevented water from the surrounding area from flowing onto the plots. The other end was open, which allowed water of major storms to flow from the plots, thus resulting in conditions similar to those on large fields in the area. The natural slope of the soil is <1% at the study area. Precipitation was measured at the plot area.

Eight cropping systems were evaluated in the study that was started in 1994 on plots that were uniformly cropped to winter wheat for the 1993–1994 season. The systems were:

1. Grain sorghum–kenaf rotation (GS–K)
2. Fall canola–winter wheat rotation (FC–W)
3. Spring canola–winter wheat rotation (SC–W)
4. Winter wheat–fallow–grain sorghum–fallow rotation (WSF)
5. Continual grain sorghum (CGS)
6. Continual winter wheat (CW)
7. Continual triticale (CT)
8. Opportunity cropping—three series (OC-1, OC-2, and OC-3)

Opportunity crops were forage sorghum, pinto bean, oat, millet, grain sorghum, and winter wheat.

Use of three opportunity cropping series permitted greater flexibility in crops to be grown, thus providing an opportunity to compare different crops (for example, millet and forage sorghum) under generally similar conditions. Definite cropping sequences were not used for the opportunity crops. All systems were replicated three times and each phase of each system was in place each year.

The goal for opportunity cropping was to intensify cropping by planting a crop after harvesting a previous crop whenever the soil became wetted by precipitation to at least a 0.60-m depth, provided growing conditions (temperatures, potential precipitation, and length of growing season) were favorable for a crop. For example, grain sorghum or winter wheat could be planted at normal seeding dates. If conditions in summer became favorable too late for planting grain sorghum, then forage sorghum, millet, or pinto bean could be planted. Likewise, oat could be planted in late winter or early spring if wheat was not planted.

The no-tillage system was used for the WSF rotation, with weeds after harvesting wheat controlled with an application of a tank mix of atrazine[1] [6-chloro-*N*-ethyl-*N*′(1-methylethyl)-1,3,5-triazine-2,4-diamine] at 340 mg m^{-2} active ingredient (a.i.) and 2,4-D [(2,4-dichlorophenoxy)acetic acid] at 110 mg m^{-2} a.i. After harvesting sorghum, weeds were controlled with chlorsulfuron [2-chloro-*N*-[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]-carbonyl]benzenesulfonamide] applied at 3.5 mg m^{-2} a.i. The no-tillage system also was used for all opportunity cropping series, with weeds and volunteer crop plants controlled with glyphosate [*N*-(phosphonomethyl)glycine]. Sweep tillage was used for weed control in plots for the remaining cropping systems. Additional weed control, when needed, was achieved with an application of glyphosate. Propazine [6-chloro-*N,N*′-bis(1-methylethyl)-1,3,5-triazine-2,4-diamine] was applied for growing season weed control in sorghum plots.

Cultivars used in the study were 'TAM-101' winter wheat, 'DK-46' ('DK-44' in 1998) grain sorghum, 'HY Test' oat, 'Trit-1' triticale, 'Bundle King 4' forage sorghum, 'Graze King' hybrid millet, 'Bush Bean Dwarf Horticulture' (Taylor) pinto bean, 'Everglades 41' kenaf, 'A.C. Elect' spring canola, and a Polish type of fall canola. Row crops (grain sorghum, pinto bean, kenaf, and canola) were planted with a John Deere Max-Emerge planter in 0.75-m spaced rows. Other crops were drill planted in 0.25-m spaced rows. Planting dates (Table 1) for a given crop varied among years because planting was done after adequate rain occurred during the period suitable for the crop. Planting rates were 40 kg ha^{-1} seed for wheat, triticale, and oat; 6 kg ha^{-1} for fall and spring canola, millet, and forage sorghum; and 8 kg ha^{-1} for kenaf. Grain sorghum was planted at a rate to obtain about 85 000 plants ha^{-1}. Planting depths were 4 to 5 cm for all crops, except canola, which was planted at a depth of 1 to 2 cm.

Because the study area previously was used for irrigated crops, the soil nutrient status was determined and N fertilizer was applied at a 50 kg ha^{-1} rate, which is considered adequate for dryland crops on Pullman soil. Phosphorus and K fertilizers are not required for dryland crops on a Pullman soil.

Wheat, oat, triticale, forage sorghum, millet, and kenaf yield samples were obtained by cutting plants at 1 to 2 cm above the soil surface from two 1-m^2 areas per plot. For grain crops, plants were air-dried, then threshed to separate grain from the plant residues. Yields of grain and plant residues were determined and are reported on an air-dried weight basis. For forage crops, samples were weighed; subsamples were taken, weighed, oven-dried at 60°C, and weighed again; and yields were calculated and are reported on an oven-dried weight basis. For grain sorghum, pinto bean, and canola, samples were taken from two 3-m long sections of two rows. Grain sorghum head samples were taken first, then plants were cut at 1 to 2 cm above the soil surface. Sorghum head samples and plant subsamples were oven-dried at 60°C. Sorghum yields are reported on an oven-dried weight basis. Pinto bean yields are reported on an air-dried weight basis. Canola did not produce grain.

Soil plant-available water contents were determined gravimetrically, then converted to a volumetric basis. The water content at the 1.5-MPa matric potential was used as the lower limit of water availability to plants. Samples were taken at planting and harvesting of each crop with a hydraulically powered, tractor-mounted core sampler to a 1.8-m depth by 0.30-m increments. The samples were oven-dried at 105°C.

Samples for soil organic carbon concentration (SOCC) and aggregation were obtained by hand sampling at depths of 0 to 5, 5 to 10, and 10 to 15 cm at the start and end of the study at three sites per plot. Soil from the three sites was composited into one sample separately for each depth. The soil was passed through a screen having 12.7-mm openings, air-dried, and stored in closed containers until making the determinations.

[1] The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by the USDA-ARS. Mention of a pesticide does not constitute a recommendation for use nor does it imply registration under FIFRA as amended.

Table 1. Planting and harvesting dates for dryland crops, Bushland, TX, 1994–1998. (Note: for wheat, triticale, and fall canola, harvesting occurred in the year after the year shown in the column headings.)

Crop	Year				
	1994	1995	1996	1997	1998
Wheat	23 Sept./29 June	16 Oct./14 June	25 Sept./10 July	30 Sept./10 June	NP†
Triticale	23 Sept./14 July	16 Oct./3 July	25 Sept./10 July	30 Sept./10 June	NP
Fall canola	23 Sept./29 June	16 Oct./NH‡	25 Sept./NH	30 Sept./21 July	NP
Grain sorghum	NP	10 July/15 Nov.	NP	6 June/4 Nov.	1 June/30 Oct.
Kenaf	NP	19 June/15 Nov.	22 July/15 Nov.	6 June/4 Nov.	1 June/30 Oct.
Spring canola	NP	15 May/8 Aug.	NP	3 Mar./10 July	6 Apr./21 July
Opportunity crops—Series OC-1					
Pinto bean	1 Aug./4 Oct.	NP	NP	NP	NP
Forage sorghum	NP	19 June/ 6 Sept.	NP	NP	NP
Millet	NP	NP	22 July/30 Sept.	NP	NP
Oat	NP	NP	NP	5 Mar./11 July	NP
Spring canola	NP	NP	NP	NP	6 Apr./21 July
Opportunity crops—Series OC-2					
Forage sorghum	1 Aug./10 Oct.	NP	22 July/30 Sept.	NP	NP
Millet	NP	19 June/ 6 Sept.	NP	NP	NP
Grain sorghum	NP	NP	NP	6 June/4 Nov.	NP
Pinto bean	NP	NP	NP	NP	27 May/30 Oct.
Opportunity crops—Series OC-3					
Wheat	23 Sept./29 June	NP	NP	NP	NP
Grain sorghum	NP	10 July/15 Nov.	NP	NP	NP
Millet	NP	NP	22 July/30 Sept.	NP	NP
Oat	NP	NP	NP	5 Mar./11 July	NP
Spring canola	NP	NP	NP	NP	6 Apr./21 July

† Crop not planted.
‡ Crop not harvested.

The SOCC was determined on duplicate subsamples by a high-temperature combustion method using a Leco CNS-2000 Analyzer (Leco Corp., St. Joseph, MI).

Duplicate subsamples of bulk soil were wetted under a vacuum to determine water-stable aggregate size distribution according to Kemper and Rosenau (1986). From these determinations, aggregate mean weight diameter (MWD) and percentage of aggregates <0.25 mm in diameter were calculated. A portion of the bulk soil was sieved to obtain 1.0- to 2.0-mm diameter aggregates. The stability in water of duplicate subsamples of these aggregates was determined by Kemper's (1965) procedure. Values of all duplicate subsample determinations were averaged before analyzing the data.

Soil bulk density was determined at the start and end of the study. Core samples 54 mm in diameter were obtained at three sites per plot with a hydraulically powered, tractor-mounted sampler at depths of 0 to 5, 5 to 10, 10 to 20, 20 to 35, 35 to 50, and 50 to 65 cm.

The study had a randomized complete block design. Data were analyzed by the analysis of variance technique (SAS Inst., 1989). Separate analyses were made for systems involving grain sorghum or winter wheat to determine cropping system effects on soil water contents, water use, crop yields, and water use efficiencies. Other crops had no direct comparison and results were analyzed only to determine the year effect. For SOCC, aggregation, and bulk density data, values from all systems were included in a common analysis, with separate analyses made for each soil depth. When different at the $P \leq 0.05$ level of probability, means were separated by the protected least significant difference (LSD) method.

RESULTS AND DISCUSSION

Precipitation

Annual precipitation during the study was near the long-term (1939–1997) average (Table 2). Maximum deviations were +5% in 1995 and −10% in 1998. Although annual totals were near the long-term average, major deviations from long-term monthly averages occurred within years. During the 5-yr period, precipitation was less than half the average in 24 mo, with precipitation being 0 or 1 mm in 10 mo. Extended low precipitation periods occurred from November 1994 through April 1995 (6 mo) when the total was 51 mm and from October 1995 through May 1996 (8 mo) when the total was 62 mm. Those droughty periods resulted in low winter wheat and triticale yields. The second one also resulted in inadequate soil water storage and seed zone soil water contents for timely planting of grain sorghum (grain sorghum not planted in 1996). The low and erratic precipitation caused difficulty in or nonestablishment of fall and spring canola in some cases.

From December 1996 through March 1997, total precipitation was 12 mm. Such low total during that period is common because winter precipitation in the region normally is low. A more critical low precipitation period occurred from April through September 1998 when the total was 122 mm, which was about one-third of the long-term average. For June, which on average receives the most precipitation in the region, the total was 1 mm in 1998.

A period of much above average precipitation occurred from July through September 1996, for which the total was 352 mm (76% of the year's total). Other months with much above average total precipitation were July 1994, May 1995, April 1997, and October 1998.

The highly variable precipitation within years and growing seasons of the different crops resulted in crop failures (or crop not planted) in some cases and good yields in other cases. More details regarding yields are given in the Results and Discussion section. Average precipitation amounts during the growing season of the different crops are given in Tables 3, 5, 6, and 8.

Table 2. Precipitation during the study period and the long-term average at Bushland, TX (climatic records, USDA-ARS Conservation and Production Research Laboratory, Bushland, TX).

Month	Year						
	1994	1995	1996	1997	1998	Avg.	Long-term avg. (1939–1997)
	mm						
January	7	11	1	4	2	5	13
February	1	1	4	7	30	9	13
March	30	20	1	0	52	21	20
April	39	9	0	123	10	34	28
May	59	123	17	50	44	59	68
June	49	60	55	25	1	38	75
July	122	96	159	27	29	87	68
August	65	59	132	80	37	75	72
September	43	80	61	28	1	43	49
October	46	20	11	19	193	58	39
November	5	1	19	18	21	13	14
December	5	18	1	46	5	15	15
Totals	471	498	461	427	425	457	474

Wheat Cropping Systems

Average soil water content was highest for the WSF system, intermediate for the FC–W, and similarly lowest for the CW and SC–W systems at wheat planting time (Table 3). The higher water content for the WSF system resulted from consistently more time from harvesting of the previous crop (grain sorghum) until wheat planting (300–330 d). Although the FC–W system was planned to result in a crop each year (canola or wheat) with about 100 d between harvesting of one crop and planting of the next, canola did not become established in two cases because of inadequate precipitation at planting time. In those cases, the FC–W system became a wheat–fallow (WF) system, which provided more time than the WSF system for storing soil water. Soil water storage resulting from use of a WF system (one crop in 2 yr) in the region, however, is inefficient, and Jones and Popham (1997) showed storage with it to be similar to that with the WSF system. In this study, lower average water content at planting than with the WSF system resulted from less time between crops in the two cases when fall canola was established. Lower amounts of crop residues on the soil surface in FC–W than in WSF plots undoubtedly contributed to the lower water contents in the FC–W plots. The lower water contents at planting in CW and SC–W plots resulted from less time between crops. Precipitation in 1997 totaled 116 mm during the harvesting to planting period with the CW and SC–W systems. Water contents at planting, however, were low with those systems (32 and 42 mm, respectively) in 1997 because storms were infrequent and none produced more than 20 mm, which resulted in low water storage efficiencies.

Average soil water contents at harvesting were similar with all systems (Table 3). Soil water use (difference between contents at planting and harvesting), however, ranged from 57 mm with the SC–W system to 131 mm with the WSF system. As a result, growing season water use (soil water use plus precipitation) differed, being greatest with the WSF system, intermediate with the FC–W, and similarly lowest with the CW and SC–W systems (Table 3).

Average grain yields were similar for the WSF and FC–W systems, but both were higher than with the CW and SC–W systems for which they were similar (Table 4). Higher yields with the WSF and FC–W systems are attributed to the higher soil water contents at planting (Table 3).

Grain yields differed ($P \leq 0.001$) among years. Average yields were lower for the 1994–1995 and 1995–1996 crops than for the 1996–1997 and 1997–1998 crops. Prospects were good for high grain yields for the 1994–1995 crop, but a late freeze severely damaged the crop. Low yields for the 1995–1996 crop resulted from low precipitation from October 1995 through May 1996 (Table 2). Late growing season (April and May) precipitation greatly benefited the 1996–1997 crop. Generally good precipitation throughout the growing season resulted in the good yields for the 1997–1998 crop.

The year by cropping system interaction effect for grain yield was significant (Table 4). Yields did not differ among systems for the 1994–1995, 1995–1996, or

Table 3. Wheat cropping systems data on plant-available soil water content, harvest index, precipitation, water use, and water use efficiency, Bushland, TX, 1994–1998. (Note: wheat grain and residue yields are given in Table 4).

Factor	Cropping system				LSD (0.05)
	WSF†	CW	FC–W	SC–W	
Soil water at planting, mm	183	127	165	115	17
Soil water at harvest, mm	52	53	52	58	NS
Harvest index	0.25	0.24	0.28	0.23	–
GS precipitation, mm	211	211	211	211	–
GS water use, mm	342	285	324	268	18
WUE (grain), kg m^{-3}	0.52	0.46	0.58	0.41	0.06
WUE (residue), kg m^{-3}	1.55	1.44	1.51	1.38	0.10

† WSF, wheat–fallow–sorghum–fallow; CW, continual wheat; FC–W, fall canola–wheat; SC–W, spring canola–wheat; NS, not significant; GS, growing season; LSD, protected least significant difference; WUE, water use efficiency.

Table 4. Wheat grain and residue yields, Bushland, TX.

Crop year	WSF†	CW	FC–W	SC–W	Avg.
	Cropping system				
	Grain yield, Mg ha^{-1}				
1994–1995	0.57	0.76	0.35	0.63	0.57
1995–1996	1.19	0.51	1.49	0.46	0.91
1996–1997	2.33	2.45	2.31	2.29	2.34
1997–1998	2.99	1.57	3.34	1.00	2.23
Avg.	1.77	1.32	1.87	1.09	
LSD ($P \leq 0.05$ level) for crop year averages = 0.37 Mg ha^{-1}, for cropping system averages = 0.39 Mg ha^{-1}, and for year × system interaction = 1.85 Mg ha^{-1}					
	Residue yield, Mg ha^{-1}				
1994–1995	5.0	5.1	4.0	4.4	4.6
1995–1996	2.9	2.0	2.3	1.0	2.1
1996–1997	5.9	5.2	5.6	5.7	5.6
1997–1998	7.3	4.0	7.5	3.8	5.6
Avg.	5.3	4.1	4.9	3.7	
LSD ($P \leq 0.05$ level) for crop year averages = 0.7 Mg ha^{-1}, for cropping system averages = 0.6 Mg ha^{-1}, and for year × system interaction = 3.2 Mg ha^{-1}					

† WSF, wheat–fallow–sorghum–fallow; CW, continual wheat; FC–W, fall canola–wheat; SC–W, spring canola–wheat; LSD, protected least significant difference.

1996–1997 crops, but differed for the 1997–1998. Some differences between these high yields for the 1997–1998 crop and yields for the 1994–1995 and 1995–1996 crops also exceeded the LSD value for the interaction effect.

Average residue yields followed the same patterns as for grain yields, with differences being significant for the same systems (Table 4). Conditions affecting average grain yields also affected average residue yields (over years). However, average residue yield was 4.6 Mg ha^{-1} for the 1994–1995 crop, which should have resulted in a higher average grain yield than the 0.57 Mg ha^{-1} obtained. The late freeze greatly reduced grain yield, but had little effect on residue yield.

The year × cropping system interaction effect for residue yield was significant, with the LSD = 3.2 Mg ha^{-1}. Yields did not exceed this value for the 1994–1995, 1995–1996, or 1996–1997 crops, but exceeded it for the 1997–1998 crop when they were lower with the CW and SC–W than with other systems. Some differences between the high yields with the WSF and FC–W systems for the 1997–1998 crop and those with some systems for 1994–1995 and 1995–1996 also exceeded the LSD value for the interaction effect.

Average harvest indexes (Grain yield ÷ Total aboveground dry matter) differed little because of cropping systems (Table 3), but tended to be higher for the FC–W than for other systems. All harvest indexes were relatively low, largely because of results for the 1994–1995 crop when grain yields were greatly reduced by the late freeze whereas the freeze had little effect on residue yields.

Water use efficiency (WUE) for grain production (Grain yield ÷ Growing season water use) was highest with the FC–W system, intermediate with the WSF, and lowest with the CW and SC–W systems (Table 3). Higher WUE with the FC–W than with other systems resulted from the combined effect of the trend toward higher grain yield and lower growing season water use (some yield and water use differences for the FC–W and other systems were not significant).

Table 5. Grain sorghum cropping systems data on plant-available soil water content, yield, harvest index, precipitation, water use, and water use efficiency, Bushland, TX, 1995, 1997, and 1998 (drought in 1996).

Factor	WSF†	CGS	GS–K	LSD (0.05)
	Cropping system			
Soil water at planting, mm	206	188	181	NS
Soil water at harvest, mm	69	66	60	NS
Grain yield, Mg ha^{-1}	2.89	3.02	2.24	0.61
Residue yield, Mg ha^{-1}	2.3	1.9	1.9	0.4
Harvest index	0.56	0.62	0.55	–
GS precipitation, mm	163	163	163	–
GS water use, mm	300	285	284	13
WUE (grain), kg m^{-3}	0.96	1.06	0.79	0.08
WUE (residue), kg m^{-3}	0.77	0.67	0.67	0.09

† WSF, wheat–fallow–sorghum–fallow; CGS, continual grain sorghum; GS–K, grain sorghum–kenaf; LSD, protected least significant difference; NS, not significant; GS, growing season; WUE, water use efficiency.

Although total water use during the growing season was highest with the WSF system, that system resulted in the highest WUE for residue production (Residue yield ÷ Total water use) because residue yield was highest with that system. Residue yield, water use, and WUE were lowest with the SC–W system. The highest and lowest WUEs for residue production were not different from those for some other systems (Table 3).

Grain Sorghum Cropping Systems

Soil water contents at grain sorghum planting and harvesting were not different because of systems used (Table 5) (the content at planting differed at the P = 0.07 level). Grain yield, however, was higher with WSF and CGS systems than with the GS–K system and residue yield was higher with the WSF system than with CGS and GS–K systems. Also, growing season water use was greater with the WSF than with other systems. Greater water use contributed to the higher grain and residue yields with the WSF system. Grain yields with CGS and WSF systems were similarly high, but growing season water use was lower with the CGS than with the WSF system. As a result, WUE for grain production was highest with the CGS system.

Except when grain sorghum was not planted in 1996 because of the drought, all crops were grown as planned each year on all plots of cropping systems that involved grain sorghum. The average grain and residue yields given in Table 5 are for years other than 1996. Grain yield was lower with the GS–K than with the WSF and CGS systems. Average soil water contents at planting and harvesting and average growing season water use, however, were not different for these systems. Although soil water contents and uses were not different, sorghum yields with the GS–K system tended to be lower than with other systems (2.94, 3.08, and 2.32 Mg ha^{-1} for WSF, CGS, and GS-K systems, respectively, in 1997; 1.91, 2.38, and 0.95 Mg ha^{-1} for the respective systems in 1998). Kenaf was grown the previous year in both cases. This suggests slightly lower soil water contents at planting (15–21 mm in 1997 and 18–39 mm in 1998; not significant) reduced sorghum yields as compared with yields with other systems when sorghum was planted after kenaf.

Table 6. Plant-available soil water content, yield, precipitation, water use, and water use efficiency data for cropping systems involving alternative crops, Bushland, TX.

	Cropping systems											
	GS–K†			FC–W			SC–W			Continual crops		
Factor	Kenaf	Sorghum	LSD	Fall canola	Wheat	LSD	Spring canola	Wheat	LSD	Triticale	Wheat	LSD
Soil water at planting, mm	193 (160)‡	181	NS	140	161 (165)	19	171	116 (115)	23	Note§	Note	Note
Soil water at harvest, mm	40 (50)	60	18	133	83 (52)	11	23	67 (58)	16	Note	Note	Note
Grain yield, Mg ha^{-1}	–	2.24	–	–	1.33 (1.87)	–	–	1.31 (1.09)	–	Note	Note	Note
Residue/forage yield, Mg ha^{-1}	1.5 (2.3)	1.9	NS	–	4.8 (4.9)	–	1.8	4.1 (3.7)	0.9	Note	Note	Note
Growing season precipitation, mm	163 (192)	163	–	262	272 (211)	–	176	255 (211)	–	239	211	–
Growing season water use, mm	316 (302)	284	22	269	350 (324)	17	324	304 (268)	17	321	285	22
WUE (grain), kg m^{-3}	–	0.79		–	0.38		–	0.43		0.34	0.46	0.10
WUE (residue/forage), kg m^{-3}	0.5	0.7		–	1.4		0.6	1.3		1.4	1.4	
WUE (total plant material), kg m^{-3}	0.5	1.5		–	1.8		0.6	1.8		1.8	1.9	

† GS–K, grain sorghum–kenaf; FC–W, fall canola–wheat; SC–W, spring canola, wheat; LSD, protected least significant difference; WUE, water use efficiency; NS, not significant.
‡ Values in parentheses are average for all years. Other values are for years when both crops were grown.
§ Soil water and yield data for triticale and wheat are given for individual crop years in Table 7.

The trend toward a lower soil water content at planting with the GS–K than with the CGS system (different at the $P = 0.07$ level) possibly was related to surface cover provided by residues of the previous crop. Residues of both crops were retained on the surface and, on a weight basis, the amount was greater for kenaf (2.3 Mg ha^{-1}, Table 6) than for sorghum (1.9 Mg ha^{-1}, Table 5). However, kenaf has a woody stem and its leaves apparently decompose readily (kenaf has a high protein content, given later). Therefore, surface coverage with kenaf may have been less than where the previous crop was sorghum, which has a pithy stem with leaves more resistant to decomposition. Soil water evaporation decreases with increases in surface coverage provided by crop residues (Unger and Parker, 1976) and soil water storage between crops, therefore, tended to be greater in CGS than in GS–K plots.

Sorghum residue yield was greater with the WSF than with other systems, with the increase attributable to the greater growing season water use (Table 5). Although water use was greater with the WSF system, the increase in residue production was sufficient to result in greater WUE for residue production with the WSF than with other systems.

Alternative Crops in Cropping Systems

Results for alternative crops were not compared directly with each other, but with results for companion crops within cropping systems (Tables 6 and 7). Comparisons for a system are based on results for years when both crops were grown. Those results are the first ones given in columns for kenaf and wheat. Grain sorghum and spring canola were not planted because of the drought in 1996. Although planted, the 1995–1996 and 1996–1997 fall canola crops did not become established because of rapid soil drying after planting. Values within parentheses for kenaf and wheat are for all years. Results for continual triticale and continual winter wheat were compared also.

Grain Sorghum–Kenaf (GS–K)

Soil water contents were similar at planting and only 20 mm higher in grain sorghum than in kenaf plots at harvesting (Table 6). The small differences are logical

Table 7. Plant-available soil water contents at planting and harvesting and grain yields for triticale and winter wheat at Bushland, TX.

	Crop		
Crop year	Triticale	Wheat	Average
	Soil water content at planting, mm		
1994–1995	121	124	123
1995–1996	141	177	159
1996–1997	162	177	170
1997–1998	15	32	24
Avg.	110	127	
LSD ($P \leq 0.05$ level) for crop year average = 10 mm, for crop average = 17 mm, and for year × crop interaction = NS†			
	Soil water content at harvesting, mm		
1994–1995	35	116	75
1995–1996	32	15	23
1996–1997	16	32	24
1997–1998	27	48	37
Avg.	27	53	
LSD ($P \leq 0.05$ level) for crop year average = 29 mm, for crop average = 14 mm, and for year × crop interaction = 65 mm			
	Grain yields, Mg ha^{-1}		
1994–1995	1.76	0.76	1.26
1995–1996	0.06	0.61	0.34
1996–1997	2.25	2.45	2.35
1997–1998	0.30	1.57	0.94
Avg.	1.09	1.35	
LSD ($P \leq 0.05$ level) crop year average = 0.53 Mg ha^{-1}, for crop average = 0.22 Mg ha^{-1}, and for year × crop interaction = 1.04 Mg ha^{-1}			
	Residue yields, Mg ha^{-1}		
1994–1995	6.2	5.1	5.7
1995–1996	1.7	2.0	1.9
1996–1997	6.7	5.2	6.0
1997–1998	4.1	4.0	4.1
Avg.	4.7	4.1	
LSD ($P \leq 0.05$ level) crop year average = 0.6 Mg ha^{-1}, for crop average = 0.5 Mg ha^{-1}, and for year × crop interaction = NS			

† Not significant.

because planting and harvesting dates were the same for both crops. Growing season water use, however, was greater for kenaf because of the trend toward a greater content at planting and a lower content at harvesting than for sorghum. Although growing season water use was greater, plant material (no grain produced) yield by kenaf was less than residue yield by sorghum. Sorghum also produced grain, thus producing more than twice as much total plant material as kenaf. The WUE for total plant material production for sorghum was three times that for kenaf (Table 6). These results indicate kenaf is not well suited as a dryland crop for the region.

Grain sorghum was not planted in 1996 because the drought persisted until after the cutoff date for planting the crop. However, rains began in July and kenaf was planted on 22 July. Growing season rainfall for kenaf totaled 277 mm in 1996, well above the average for other years (Table 6). As a result, kenaf grew rapidly and reached heights of 0.55 m by 23 August, 1.5 m by 25 September, and 1.6 m by 18 October (no change by 15 November; killed by frost on 18 October). Protein concentrations on the respective dates were 327, 213, 195, and 176 g kg^{-1}. Final dry plant material yield was 3.9 Mg ha^{-1}. Such yield along with its favorable protein content indicates that kenaf may be adaptable as a dryland crop to regions having more dependable rainfall. As such, it could provide a high-quality forage for livestock (Nielsen 1998; Phillips et al., 1996; Webber, 1993).

Fall Canola–Wheat (FC–W)

Fall canola was planted each year, but became established only for the 1994–1995 and 1997–1998 crop years, whereas wheat was planted and became established each year. Total profile and seed zone soil water contents at planting were suitable for both crops each year (Table 6). However, because of the small seed size, canola was planted shallower than wheat (Table 1), which caused canola establishment to fail when dry, windy weather after planting rapidly dried the seed zone soil.

Even when established, canola growth was poor, grain (seed) was not produced, and plant material production was extremely low and not determined. In contrast, wheat yielded 1.33 Mg ha^{-1} grain and 4.8 Mg ha^{-1} residue for the crop years when canola was established. The poor growth of fall canola is reflected in the soil water contents at planting and harvesting. Canola extracted less water from soil than wheat, which resulted in a greater water content at planting for wheat than for canola. The profile was not filled to capacity with water for either crop because of the short period between harvesting in June or July and planting in late September. The poor growth of canola resulted in the average soil water content at harvesting being only 7 mm less than at planting. Also, growing season water use for canola was 81 mm less than for wheat. Under conditions of this study, fall canola was not a viable alternative dryland crop for the region. However, a comprehensive study involving such factors as different varieties, planting dates, and planting depths is needed to fully ascertain the potential of fall canola as a dryland crop for the region.

Spring Canola–Wheat (SC–W)

Spring canola was planted and became established each year, except in 1996 because of the drought. As for fall canola, spring canola growth was poor and it produced no grain and little other plant material (Table 6). Failure to produce grain probably resulted from floral or pod abortion due to high air temperatures at a critical growth stage. In contrast, wheat yields averaged 1.31 Mg ha^{-1} grain and 4.1 Mg ha^{-1} residue.

The soil water contents at planting reflect the different times for planting the crops. Wheat planting was in fall about 90 d after harvesting canola. This provided relatively little time for soil water storage and resulted in the low water content at wheat planting. In contrast, canola was planted in spring about 300 d after wheat harvesting. This provided more time for water storage and, hence, the higher water content at canola planting (Table 6).

The lower water content at canola than at wheat harvesting reflects the differences in growing season lengths and harvesting dates. Canola harvesting (plant material other than grain) was between 10 July to 8 August, whereas wheat harvesting was between 10 June and 10 July. The later harvesting resulted in greater water extraction by canola (148 mm) than by wheat (49 mm) and, hence, the lower content at canola harvesting (Table 6).

Precipitation was lower during the canola growing season (85–128 d) than the wheat growing season (241–288 d) (Table 6). However, because soil water extraction was greater, total growing season water use also was greater by canola than by wheat.

Spring canola became established each year when planted and used more water than wheat, but failed to produce grain. Hence, as for fall canola, a comprehensive study involving different varieties, planting dates, and planting depths is needed to fully ascertain the potential of spring canola as a dryland crop for the region.

Continual Triticale–Continual Wheat (CT–CW)

Average soil water contents at planting and harvesting were greater in wheat than in triticale plots (Table 7), with the differences resulting from the longer growing season for triticale. Both crops were planted on the same date each year. Also, both crops were harvested on the same date in 2 yr, but triticale was harvested 15 d later than wheat in 1995 and 19 d later in 1996. As a result, soil water extraction was greater by triticale than by wheat and time for soil water storage was shorter after triticale. These differences resulted in greater growing season water use by triticale than by wheat (Table 6).

Although average growing season water use was greater by triticale than by wheat, average grain yield was lower for triticale (Table 7). Yield differences for the 1994–1995 crop resulted from late-season freezing weather that severely damaged wheat, but not triticale because it was at a less advanced growth stage when the freeze occurred. The low yield for the 1995–1996 crop is attributed to the longer growing season that resulted in greater water stress because of low rainfall during the grain-filling period. Wheat yields were low for that crop also. Yields were similar for both crops for the 1996–1997 season. For the 1997–1998 season, both crops were harvested on the same date, but yields were lower for triticale, which suggests triticale was affected to a greater extent than wheat by low rainfall (Table 2). Head development was poor for triticale for 1997–1998. The year × crop interaction was significant because of the differences given above.

Residue production was higher for triticale than for wheat (Table 7). Much of the winter wheat in the region is grazed by livestock in late fall, winter, and early spring, with some of it grazed out rather than harvested for grain. Higher residue production by triticale, along with the longer growing season, therefore, could be of benefit when the crop is grazed by livestock rather than harvested for grain. The longer growing season would extend the grazing period of a winter crop and, hence, provide more time for a spring or early summer crop to become suitable for grazing.

Because of the lower yield and greater growing season water use, the WUE for grain production was lower for triticale than for wheat (Table 6). The WUEs for continual wheat and wheat in other cropping systems were similar. For forage production, WUEs were identical for triticale and wheat. Also, WUEs for total dry matter production for continual triticale, continual wheat, and wheat in other cropping systems were similar.

Opportunity Crops

Opportunity crops were planted when the soil became wetted by precipitation to at least the 0.6-m depth after harvesting a previous crop. The lowest water content was at millet planting in 1996 in Series 3 plots (Table 8). In that case, the previous crop was grain sorghum, which was harvested in November 1995. That late harvest coupled with low precipitation through June 1996 (Table 2) resulted in little, if any, soil water storage before above average rainfall in July 1996. Hence, the low water content at millet planting.

Other opportunity crops planted in 1996 were millet in Series 1 plots and forage sorghum in Series 2 plots. For these crops, water contents higher than for millet in Series 3 plots (Table 8) resulted from the earlier harvest (6 September) of the previous crops (forage sorghum in Series 1 and millet in Series 2 plots), which provided for some soil water storage from the September and October precipitation (Table 2).

The two highest soil water contents were at spring canola planting in April 1998 in Series 1 and Series 3 plots (Table 8). In both cases, the previous crop was oat harvested in July 1997. The next highest water content was at pinto bean planting in May 1998 in Series 2 plots for which the previous crop was grain sorghum harvested in November 1997. The lower water content at planting in 1998 in Series 2 than in Series 1 and 3 plots resulted from less time since harvest of the previous crop. Although water contents were highest at planting for crops in all series in 1998, the crops produced no grain, mainly because rainfall during the growing season was below the long-term average in all months (Table 2). Total rainfall from 1 Apr. 1998 through 30 Sept. 1998 was 122 mm, the lowest on record for that period at the USDA-ARS Laboratory at Bushland.

Besides the lowest and three highest water contents, other water contents at planting ranged from 108 mm for grain sorghum in Series 3 plots in 1995 to 205 mm for grain sorghum in Series 2 plots in 1997. These water contents indicate the soil was wetted to a depth of at least 0.9 m (Pullman soil retains about 230 mm of plant-available water at field capacity [0.033 MPa matric potential] to a depth of 1.8 m).

Soil water contents at harvesting were strongly influenced by rainfall late in the growing season. In most cases, contents at harvesting were much lower than at planting. Exceptions were for wheat in Series 3 plots in 1995 and for crops in all series in 1996. In 1995, the high content at wheat harvesting on 29 June and some early July rain provided adequate soil water for planting grain sorghum on 10 July, which was the shortest interval between crops in the study.

Table 8. Planting and harvesting date, soil water content, precipitation, water use, yield, and water use efficiency data for opportunity crops, Bushland, TX.

Crop	Year	Date: Plant	Date: Harvest	Soil water content: Plant	Soil water content: Harvest	Precip.†	Water use	Yield: Grain	Yield: Forage	WUE: Grain	WUE: Forage
				mm				Mg ha^{-1}		kg m^{-3}	
					Series 1						
Pinto bean	1994	1 Aug.	4 Oct.	125	54	145	216	2.21	–	1.02	–
Forage sorg.	1995	19 June	6 Sept.	177	54	173	296	NA	9.2	NA	3.1
Millet	1996	22 July	30 Sept.	135	120	264	279	NA	1.0	NA	0.4
Oat	1997	5 Mar.	11 July	135	85	221	271	2.36	5.3	0.87	2.0
Spr. canola	1998	6 Apr.	21 July	280	36	77	321	–	1.4	–	0.4
					Series 2						
Forage sorg.	1994	1 Aug.	4 Oct.	126	60	145	211	NA	6.4	NA	3.0
Millet	1995	19 June	6 Sept.	180	64	173	289	NA	8.9	NA	3.1
Forage sorg.	1996	22 July	30 Sept.	145	166	264	243	NA	1.2	NA	0.5
Grain sorg.	1997	6 June	4 Nov.	205	79	178	304	3.12	2.1	1.03	0.7
Pinto bean	1998	27 May	30 Oct.	219	70	132	281	–	0.2	–	0.1
					Series 3						
Winter wh.	1994–95	23 Sept.	29 June	110	97	280	293	1.08	–	0.37	–
Grain sorg.	1995	10 July	15 Nov.	108	42	180	246	2.17	1.3	0.88	0.5
Millet	1996	22 July	30 Sept.	90	118	264	236	NA	1.1	NA	0.5
Oat	1997	5 Mar.	11 July	123	79	221	265	2.16	5.0	0.82	1.9
Spr. Canola	1998	6 Apr.	21 July	248	13	77	312	–	1.6	–	0.5

† Precip., precipitation; WUE, water use efficiency; sorg., sorghum; spr., spring; wh., wheat; NA, not applicable.

In 1996, the water content at millet harvesting in Series 1 plots was 15 mm less than at planting. Also in 1996, water contents in Series 2 plots at forage sorghum harvesting and Series 3 plots at millet harvesting were higher than at planting. In the fall of 1996, total soil water contents in plots of all series were adequate for planting winter wheat, but seed zone water contents were too low for wheat establishment and no crop was planted until the next year.

Crop yields were highly variable (Table 8). Pinto bean yielded favorably in 1994, but failed in 1998. The different responses resulted from rainfall amount and timeliness differences (Table 2). Forage sorghum and millet yielded favorably in 1994 and 1995, but poorly in 1996. Poor yields in 1996 resulted from the short growing season because of the late planting (after the rains started in July). Oat grain and forage yields were favorable. Oat was an opportunity crop only in 1997, and a comparison among years was not possible. Grain sorghum also yielded favorably in 1997. Rainfall distribution was generally favorable in 1997 (Table 2). Grain sorghum also yielded well in 1995, even though it was planted later than normal. Winter wheat was an opportunity crop only for the 1994–1995 season, and it yielded less than the average for wheat in other cropping systems, except the SC–W system (Table 4). Spring canola failed to produce grain in 1998.

Water use efficiency for grain production was similarly high for pinto bean in 1994 and grain sorghum in 1997, and lowest for wheat in 1994–1995 (Table 8). For forage production (or plant material other than grain), WUE was similarly high for forage sorghum in 1994 and forage sorghum and millet in 1995, and relatively high for oat. The WUE was lowest for pinto bean in 1998, and low for the other crops (<0.7 kg m^{-3}).

Soil Conditions

Soil bulk density, organic C concentration, water-stable aggregate size distribution (mean weight diameter [MWD] and percentage of aggregates <0.25 mm in diam.), and water stability of 1.0- to 2.0-mm diameter aggregates were determined at the start (initial sampling) and end (final sampling) of the study. Results of these determinations, where appropriate, are given in Table 9. The water stability of 1.0- to 2.0-mm diameter aggregates was not significant and is not discussed.

Soil Bulk Density

Initial bulk densities in the cropping system plots did not differ at any given depth. Mean densities were 1.23, 1.30, 1.47, 1.59, 1.67, and 1.68 Mg m^{-3} at depths of 0 to 5, 5 to 10, 10 to 20, 20 to 35, 35 to 50, and 50 to 65 cm, respectively. Final bulk densities in the plots differed ($P \leq 0.05$ level) at depths of 10 to 20 and at 20 to 35 cm. At 10 to 20 cm, density was highest with the CGS (1.53 Mg m^{-3}) and lowest with the SC–W system (1.38 Mg m^{-3}), with other system values not different from these in some cases and from each other in most other cases (data not shown). At 20 to 35 cm, density was equally highest in CGS and GS–K system plots (1.58 Mg m^{-3}) and similarly lowest in CW and SC–W systems (1.39 and 1.42 Mg m^{-3}, respectively). Again, values for some other systems did not differ from these values or from each other.

Bulk densities at depths of 0 to 5, 5 to 10, and 35 to 50 cm differed at the $P = 0.06$ level, with CGS and GS–K system values being among the highest and those with CW and SC–W systems among the lowest in most cases (data not shown). These results indicate that systems involving frequent use of grain sorghum (continual or in a 2-yr rotation) result in higher densities than other systems, probably because fewer crop residues are returned to the soil than with systems involving wheat or triticale (Tables 4, 5, 6, and 7).

Overall mean initial and final bulk densities were similar (1.49 and 1.47, respectively). However, as compared with mean initial densities, final densities were

Table 9. Soil organic C concentration, aggregate mean weight diameter, and aggregates <0.25 mm in diameter at initial and final samplings (start and end) of a cropping system study under dryland conditions, Bushland, TX.

Sampling	Depth	Treatment											
		WSF†	CW	CT	CGS	GS–K	FC–W	SC–W	OC-1	OC-2	OC-3	LSD	Mean
	cm	Organic C concentration, g kg^{-1}											
Initial	0–5	5.69	5.33	5.60	5.32	5.52	5.43	5.65	5.49	6.08	5.63	0.38	5.57
	5–10	5.73	5.35	5.37	5.55	5.47	5.41	5.53	5.47	5.72	5.58	NS	5.52
	10–15	5.63	5.26	5.43	5.38	5.48	5.42	5.61	5.28	5.69	5.49	NS	5.47
Final	0–5	9.06	5.87	6.21	5.04	5.40	5.38	5.71	6.69	5.90	6.80	0.58	6.21
	5–10	8.31	5.97	6.25	5.05	5.45	5.35	5.39	5.56	5.72	5.85	0.44	5.89
	10–15	8.04	5.76	6.00	4.96	5.33	5.13	5.32	5.51	5.67	5.57	0.43	5.73
		Aggregate mean weight diameter, mm											
Initial	0–5	1.27	1.14	1.11	1.45	1.27	1.16	1.32	1.61	2.27	1.08	0.63	1.37
	5–10	1.85	1.66	1.66	1.65	1.68	1.75	1.83	1.49	3.43	1.78	0.72	1.88
	10–15	2.33	2.41	1.94	2.49	2.07	1.98	2.04	2.15	3.33	2.21	0.57	2.29
Final	0–5	1.37	1.53	1.74	1.08	1.40	1.22	1.31	1.54	0.98	2.14	0.51	1.43
	5–10	1.85	1.36	1.76	1.42	1.51	1.59	1.63	2.05	1.65	2.18	NS	1.70
	10–15	2.07	1.92	2.08	2.45	1.72	1.81	1.64	1.69	2.43	2.09	0.49	1.99
		Aggregates <0.25 mm diameter, %											
Initial	0–5	38.1	38.3	37.9	32.4	36.9	39.3	36.1	37.9	27.4	40.5	7.1	36.5
	5–10	29.8	32.6	31.0	32.0	32.6	32.0	30.6	34.5	17.5	32.5	6.7	30.5
	10–15	26.0	24.2	29.4	25.7	28.1	30.2	27.6	29.2	16.9	29.7	6.0	26.7
Final	0–5	45.3	40.9	37.8	44.3	42.7	47.0	44.2	41.2	48.2	40.6	5.7	43.2
	5–10	38.1	41.9	40.2	43.8	42.9	44.3	44.9	38.0	44.3	38.3	NS	41.9
	10–15	36.9	35.6	34.9	31.5	43.0	40.9	45.2	45.2	34.2	34.3	9.1	38.2

† WSF, wheat–fallow–sorghum–fallow; CW, continual wheat; CT, continual triticale; CGS, continual grain sorghum; GS–K, grain sorghum–kenaf; FC–W, fall canola–wheat; SC–W, spring canola–wheat; OC-1, opportunity cropping, Series 1; OC-2, opportunity cropping, Series 2; OC-3, opportunity cropping, Series 3; LSD, protected least significant difference.

higher at 0 to 5 cm (1.23 vs. 1.36 Mg m^{-3}, $P = 0.001$), not different at 5 to 10 (1.30 vs. 1.33 Mg m^{-3}) and at 10 to 20 cm (1.47 vs. 1.45 Mg m^{-3}), and lower at other depths (1.59 vs. 1.48 Mg m^{-3} at 20 to 35 cm, 1.67 vs. 1.57 Mg m^{-3} at 35 to 50 cm, and 1.68 vs. 1.61 Mg m^{-3} at 50 to 65 cm; $P < 0.001$ at all depths). The increase at 0 to 5 cm is attributed to soil reconsolidation because of precipitation and performance of cultural operations. The entire study area was uniformly tilled and cropped before this study was started. Bulk density decreases at depths below 20 cm may be because of greater use of small grain crops (wheat, triticale, and oat) in the study. Before this study, all plots were used for studies involving winter wheat and grain sorghum in a rotation and continual grain sorghum. As discussed above, use of grain sorghum in cropping systems tends to or does increase soil density because relatively small amounts of residues are returned to the soil.

Soil Organic Carbon Concentration (SOCC)

The initial SOCC at the 0- to 5-cm depth was higher in Series 2 opportunity cropping plots than in plots of all other cropping systems or series (Table 9), but the reason is not apparent because all plots were uniformly tilled and cropped before the study was started. The SOCCs did not differ at other depths.

The final SOCC at all depths was highest with the WSF and lowest with the CGS system (Table 9). The high SOCC with the WSF system is attributed to use of no-tillage that resulted in greater retention of crop residues on the soil surface. No-tillage also was used on opportunity cropping system plots for which SOCCs were greater than for CGS plots. The SOCCs on opportunity cropping plots, however, were lower than on WSF plots because less residue was produced or retained on opportunity cropping plots. Plant material produced by forage sorghum and millet was baled and removed from opportunity cropping plots. Other opportunity crops produced little residue as compared with that produced by wheat in other cropping systems.

The SOCCs with CW and CT systems were higher than with the CGS system, but not as high as with the WSF system. Residue production was higher with the CW and CT than the CGS system (Tables 4, 5, and 7) and, hence, the higher SOCCs. Concentrations with CW and CT systems were lower than with the WSF system because stubble mulch tillage was used on CW and CT plots, whereas no-tillage was used on WSF plots.

Wheat residue production was similar on FC–W and WSF plots and was lower on SC–W than on WSF plots. However, because canola growth and yield were poor, it produced little residue. Fall canola did not become established in 2 yr. As a result, SOCCs on FC–W and SC–W plots generally did not differ from those on CGS plots. Also, SOCCs did not differ on CGS and GS–K plots.

For means across depths, the final SOCC was higher than the initial SOCC (5.94 vs. 5.52 g kg^{-1}, $P = 0.04$). The concentrations increased with WSF, CW, and CT systems ($P = 0.0008$, 0.001, and 0.003, respectively); decreased with the CGS ($P = 0.006$); and did not change with other systems. The overall results indicate use of systems that result in greater residue production and their retention on the soil surface, as with use of no-tillage, is effective for maintaining or increasing SOCCs. When residue production is low or when residues are removed, SOCCs are not increased, even when no-tillage is used. Low residue production coupled with use of stubble mulch tillage decreases SOCCs.

Aggregate Mean Weight Diameter (MWD)

Initial aggregate MWDs at all depths were higher on Series 2 opportunity cropping (OC-2) plots than on all other plots for which they were not different (Table 9). As for SOCC at the 0- to 5-cm depth, the reason for greater MWDs on OC-2 plots is not apparent because all plots were uniformly tilled and cropped before this study was started.

Final MWDs differed at the 0- to 5- and 10- to 15-cm depths (Table 9). At 0 to 5 cm, MWDs were similarly lowest on CGS and OC–2 plots and highest on OC–3 plots. Similarly highest MWDs were on CGS and OC–2 plots and similarly lowest MWDs were on GS–K, FC–W, SC–W, and OC–1 plots at 10 to 15 cm. At those depths, values for other systems and series were not different from the low and high values in some cases and not different from each other.

The aggregate MWD results show no definite trends, except that the final MWD at 0 to 5 cm was lowest on CGS plots and highest on OC-3 plots. The SOCC also was low on CGS plots, which may have resulted in the low MWD on those plots. Mean initial and final MWDs did not differ for any cropping system or opportunity cropping series, or for the overall means.

Aggregates <0.25 mm in Diameter

The initial percentage of <0.25-mm diameter aggregates at the 0- to 5-cm depth was lowest on OC–2 plots and highest on OC–3 plots (Table 9). At other depths, it was lower on OC–2 plots than on all other plots. As for SOCC and aggregate MWD, the reason initial values on OC–2 plots at 0 to 5 cm differed from those on other plots is not apparent. Because all three variables differed on those plots, soil conditions for some unknown reason on that set of plots undoubtedly were different, even though plots were randomly assigned to the different cropping systems and opportunity cropping series.

Final percentages of <0.25-mm diameter aggregates were lowest on CT plots and highest on OC–2 plots at 0 to 5 cm, not different at 5 to 10 cm, and lowest on CGS plots and equally highest on SC–W and OC–1 plots at 10 to 20 cm. Percentages for some other systems and series did not differ from the low or high percentages and from each other. In general, no distinct trends in percentage changes due to cropping systems or opportunity cropping series occurred at any depth. However, the overall mean final percentage was higher than the initial percentage (41.1 and 31.2, respectively; $P = 0.038$). Also, final means were higher than initial means on GS–K, FC–W, SC–W, and OC–2 plots, and tended to be higher ($P \leq 0.18$) on the remaining plots, except the OC–3 plots for which $P = 0.40$.

Fine soil particles result in surface seal development (Loch, 1989) and, hence, in potentially lower water infiltration. As a result, high percentages of fine soil particles (aggregates) could thwart soil water conservation that is highly important for dryland crop production. Although Loch (1989) showed that <0.125-mm diameter materials were most important regarding seal development, materials <0.25-mm diameter are important also. Because the percentages tended to or did increase, results of this study suggest continued use of all cropping systems and opportunity cropping series could lead to higher percentages of fine aggregates. This could lead to surface seal development and, hence, decreased infiltration and lower soil water storage.

Although use of no-tillage in this study did not reduce the percentage of <0.25-mm diameter aggregates, use of no-tillage results in greater water infiltration, provided adequate residues are on the soil surface. However, when surface residue amounts are low, as often is the case under dryland conditions, a surface seal may develop, even when no-tillage is used. Under such conditions, greater water runoff may occur under no-tillage conditions than where the surface seal is disrupted by tillage (Jones et al., 1994).

CONCLUSIONS

Soil water content at crop planting and precipitation amount and distribution during the growing season strongly influenced yields of well-adapted crops (winter wheat and grain sorghum) and alternative and opportunity crops under dryland conditions in the southern Great Plains. Wheat and grain sorghum generally produced as much grain and nongrain plant material as other crops to which they were compared. Triticale yielded less grain, but more forage than wheat, suggesting that it has potential as a forage crop for grazing by livestock. Its later maturity than wheat would make it especially useful as a forage crop when it is grazed out rather than harvested for grain. Fall and spring canola did not perform well under conditions of this study because of crop establishment problems (small seeds and rapid soil drying). Kenaf has limited potential on dryland in the region because of low plant material yields. Its high protein content along with potentially higher dry matter yields, however, could make it a useful forage crop where precipitation is more reliable. Forage sorghum, millet, oat, grain sorghum, and winter wheat have potential as opportunity crops. With opportunity cropping, a crop is planted when soil water contents become favorable and climatic conditions are favorable for a given crop. As a result, opportunity cropping provides for more intensive cropping than that achieved with fixed cropping systems, thereby making more efficient use of water from precipitation than that achieved by cropping systems involving long fallow periods.

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